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CLASS 1

CYCLIC SOFTENING EFFECTS IN METALS

by

L.F. Coffin, Jr., Metallurgy and Ceramics Laboratory

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SUMMARY This report reviews the state-of-the-art relative to the effects of cyclic plastic strain on metals, with particular reference to the mechanical properties that result from this type of straining. Subjects considered include cyclic effects generally, subsequent properties, and technological applications. Particular attention is given to "mechanical annealing," that is, the phenomenon of cyclic strain softening resulting from the application of cyclic plastic strain following cold-work. For several metals, including 1100 aluminum, OFHC copper, mild steel, and 18-8 stainless, it is shown that the per cent elongation can be increased and the tensile strength decreased by cyclic straining following cold-work. The CBS (Contact-Bend-Stretch) process is utilized to effect cyclic softening in cold-worked steel strip, and it is shown that the ductility of strip so treated is enhanced in the longitudinal direction, but is unchanged in the transverse direction, when the strip is repeatedly flexed over transversely oriented small-diameter rolls.

KEY WORDS
mechanical properties, metal working, cyclic plastic strain, CBS rolling

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CYCLIC SOFTENING EFFECTS IN METALS

L.F. Coffin, Jr.

I. INTRODUCTION

The purpose of this report is to review the state-of-the-art relative to the effects of cyclic plastic strain on metals, with particular reference to the mechanical properties resulting from this type of straining. A presentation on this subject was made to the Materials Advisory Board's Committee on Metal-Working Processes and Equipment at their meeting on March 23, 1966. In preparing this material, I have included a considerable amount of unpublished data which has been in our files but is as yet unpublished, as well as work published by ourselves and others.

In the treatment of the subject the categories to be considered include (a) cyclic effects generally, (b) subsequent properties, and (c) technological applications. Under part (a) we will consider the cyclic hardening and softening behavior of metals of specific composition, the tendency to develop stabilized hysteresis loops, strain aging and softening effects as a result of cyclic straining, cyclic tension tests, and cyclic-strain induced creep. With regard to the subsequent properties, we will examine the available information with regard to changes in the flow stress curves, on the tensile strength, and on ductility as indicated by the per cent elongation or per cent reduction in area. In discussing technological applications we will be concerned primarily with the practical means for introducing cyclic plastic strain to metals so as to exploit the useful and interesting property changes that might result.

II. CYCLIC EFFECTS GENERALLY

A. Cyclic Hardening and Cyclic Softening Effects in Metals under Push-Pull Loading

In this report we are concerned with the behavior of metals subjected to controlled cyclic strain. Here, by application of the appropriate loads, the material is strained in one direction and then fully in the reverse direction so that a mechanical hysteresis loop of finite width results. The loading is shown in Fig. 1. While such a straining program can be accomplished in a number of different ways, as, for example, by reverse bending or reverse twisting, interpretation of results is somewhat more difficult than the method we will employ here, namely uniaxial loading. Controlled plastic strain experiments have been reported in the literature by many investigators, (1) the principal objective of which is to determine the resistance of metals to fatigue under such type of loading. In the course of these experiments, one can measure progressively the resistance to deformation that occurs during the cyclic loading process, against the number of cycles of stress. By this means, curves can be constructed of the stress amplitude or the stress range vs the number of cycles

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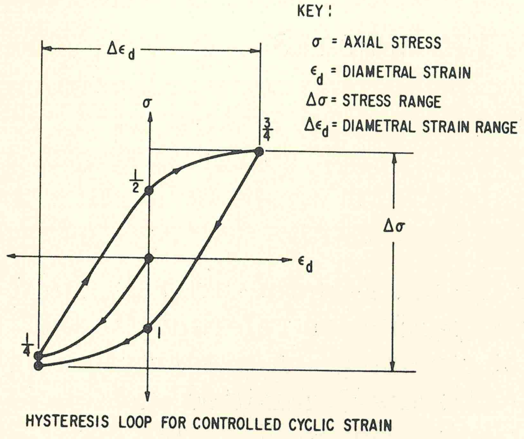
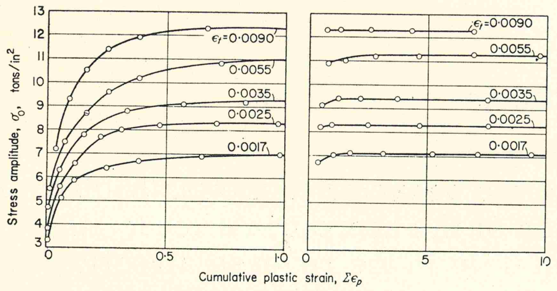


Fig. 1 Development of hysteresis loop for controlled cyclic strain.

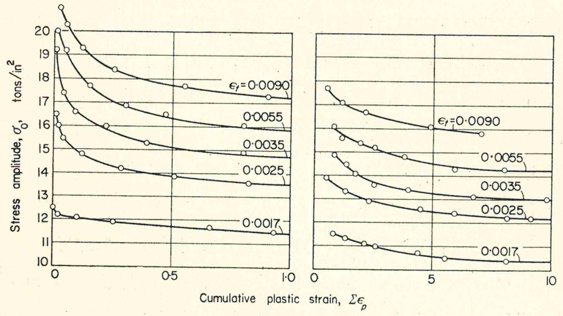
for a wide variety of materials. Some typical results are shown in Figs. 2 and 3 taken from the work of Dugdale.(2) For materials which are in the soft or annealed state and which are capable of significant strain hardening in ordinary tension tests, one finds, as a result of controlled cyclic plastic strain, that cyclic hardening occurs in the material. The hardening is characterized by a rapid increase in stress in the first few cycles followed by a progressive leveling off or saturation of the effect after many cycles of strain. When further hardening has ceased, the material is considered to have developed a stabilized hysteresis loop--that is to say, the hysteresis loop of stress versus strain repeats itself over and over again as cycling proceeds. Cyclic hardening is seen to be quite different from monotonic hardening (where the deformation occurs in one direction only, as in an ordinary tension test). Under the latter conditions, hardening increases monotonically with strain such that a relationship between stress and strain can be formulated having the form

$$\sigma = Ae^{n} \quad . \qquad (1)$$

In other words, there is no saturation in hardening.

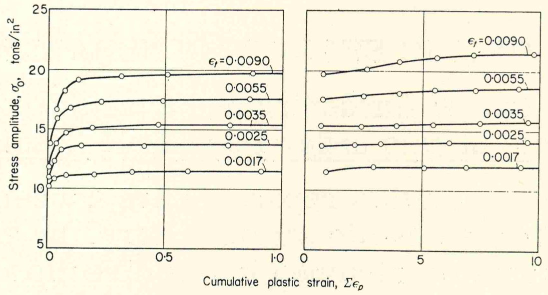


Soft copper.

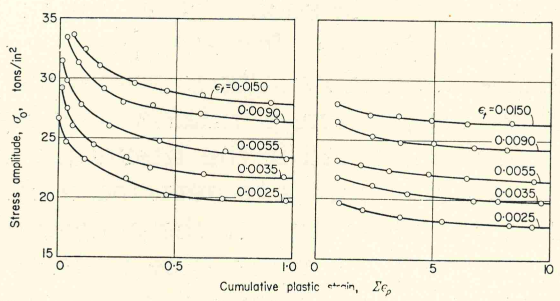


Hard copper.

Fig. 2 Cyclic hardening and softening curves--copper.



Soft steel.



Hard steel.

Fig. 3 Cyclic hardening and softening curves--steel.

The phenomenon that is of particular interest in the present discussion occurs when the material is initially in a heavily cold-worked state produced by mechanical working means of one sort or another prior to the application of cyclic plastic strain. One finds that with subsequent controlled cyclic plastic strain, cyclic softening occurs, i.e., with each further application of strain the stress reached at the point of reversal is less than that of the previous reversal. These curves are characterized by a rapid softening effect at first followed by a leveling off or a stabilizing of the hysteresis loop. These effects are to be noted in Figs. 2 and 3.

The fact that a stabilized hysteresis loop is eventually established both in the case where the material in the annealed state initially, and also with prior cold-work, raises the question as to whether the same hysteresis loop is achieved in each case. The suggestion that such would be the case was first brought forth by Polakowski.(3) Experiments which we have conducted on commercially pure aluminum, shown in Fig. 4, indicate that regardless of the initial condition of the material, the stress range reached after cycling by controlled plastic strain is the same.(4) However, it appears that this is not necessarily a general fact. It will be observed by close examination of Figs. 2 and 3, for example, that the stress amplitude reached by a given material in the soft and hard conditions for the same cyclic strain amplitude is not the same. That is, the initially hard material has not strain softened to as low a level as that to which the initially soft material has cyclically strain hardened. Differences in the height of the stabilized hysteresis loop are even more noticeable in metals that undergo pronounced strain hardening such as the austenitic stainless steels. It can be argued that the same strength level would have been reached had the material been cycled sufficiently. The intervention of a fatigue crack prevents this from occurring, however.

Indications of cyclic hardening and cyclic softening have also been found from intermittent hardness measurements made during cyclic plastic strain on annealed and cold-worked metals.(5) Figure 5 shows such measurements for an 18-8 austenitic stainless steel. From this it can be concluded that the changes observed in a push-pull test are real with respect to the bulk properties of the material.

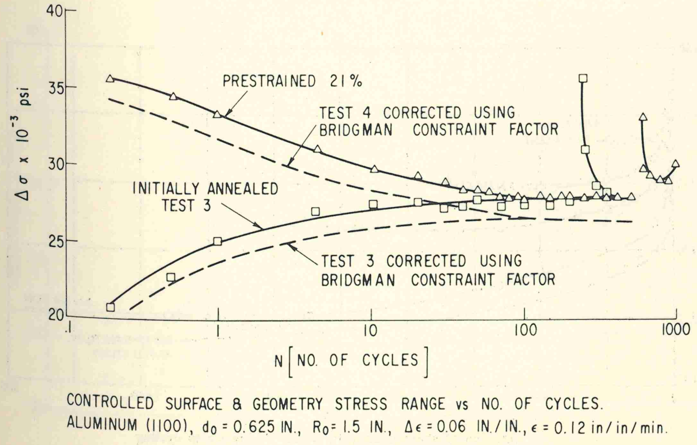


Fig. 4 Cyclic hardening and softening--1100 aluminum.

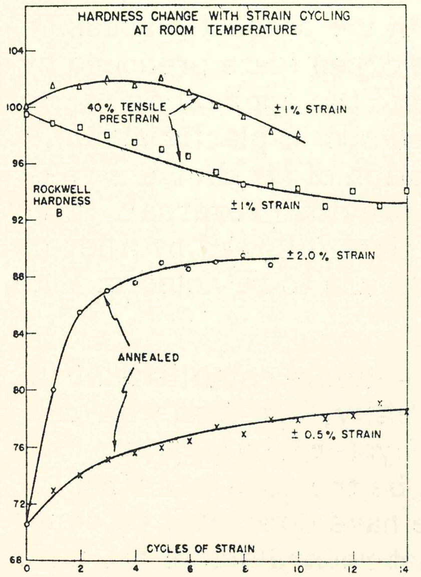


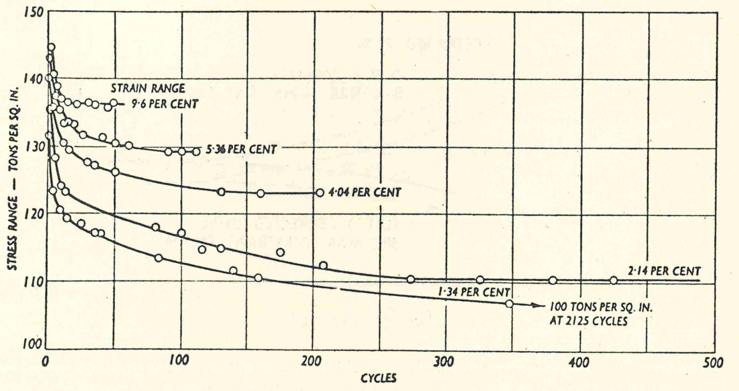
Fig. 5 Hardness variations with strain cycling at room temperature--AISI 347 stainless steel.

The existence of a stabilized hysteresis loop which depends only on the amplitude or range of strain and not on the prior state of cold work of a given material is an attractive one. It suggests that there is a characteristic microstructural state associated with application of cyclic plastic strain and that this state is achieved by progressive cyclic straining from any initial microstructural arrangement. There is no conclusive evidence with regard to this point at the present time; however, studies of subgrain structure and dislocation networks formed under cyclic strain with different initial conditions of hardness or cold-work have been helpful in trying to understand these effects.(6-8)

The cyclic hardness and softening effects described above are broadly general for materials capable of pronounced strain hardening during monotonic deformation. Results similar to those above are observed for the austentic stainless steels, nickel, titanium, etc.(9-11) On the other hand, precipitation hardened alloys show relatively little sensitivity to cyclic hardening and softening effects.(9) Here the hardening or softening may occur depending upon the initial state of heat treatment of the material. Thus, an underaged alloy will cycle harden whereas an alloy that is overaged softens.

Of particular interest is the behavior of steels which can be hardened significantly by heat treatment involving quenching and tempering. In Fig. 6, for example, is shown the behavior of a quenched and tempered steel (En 25) subjected to cyclic straining.(12) It will be noted that pronounced cyclic softening occurs much in the same manner that cold-worked structures will cycle soften. Similar effects have been reported for AISI heat-treated 4340 and AISI 52100 steels.(10) Little work has been done to understand the nature of such softening.

Fig. 6 Cyclic softening of En 25--quenched and tempered (Ref. 12).



Variation of stress range with cycles during strain cycling

B. Cyclic Strain Aging and Cyclic Softening

The discussion above has been directed primarily to those materials that are thermally stable at the temperature to which they are subjected to cyclic strain. In the present case we are concerned with the behavior of materials which undergo concurrently cyclic straining and aging effects.(13,14) An interesting example is mild steel subjected to cyclic plastic strain at temperatures around 200°C where aging can occur concurrently with the strain. Under these conditions a very rapid hardening can take place for the steel initially in the annealed state. For example, in Fig. 7 is shown the comparative cyclic hardening curves for SAE 1111 carbon steel at room temperature and at 200°C. The rapid hardening occurring at the aging temperature can be presumed to be associated with a strain-induced precipitation of carbon and nitrogen in solution on mobile dislocation sites. The effect can be greatly intensified by finding means for increasing the amount of carbon and/or nitrogen in solution prior to the aging treatment. One such procedure is to quench the material from 675°C (below the eutectoid temperature) into ice brine.(14) Subsequent cyclic strain leads to an even greater hardening as shown in Fig. 8 for two steels. One of the more interesting features of this type of hardening is revealed by the behavior of the material when subsequently cycled at room temperature. Here a pronounced cyclic softening takes place. With reference to Fig. 9, the comparative hardening and softening effects of an SAE 1111 steel cycled first at 250°C and then at room temperature are shown. It is seen that a very rapid softening occurs, and by comparison to the cyclic resistance of the material at room temperature it would appear that the hardness level will eventually reach that achieved by cycling at room temperature only. This effect is seen more convincingly perhaps in Fig. 10 where an initially annealed SAE 1111 carbon steel is considered. Here the stress range of the material cycled at room temperature is compared to the stress range obtained also at room temperature but by having been cycled either at 1% or 2% strain range for 10 cycles at 200°C. It will be noted here that the stress range reached is essentially identical for each loading sequence. The effect of these treatments on subsequent mechanical properties will be dealt with later.

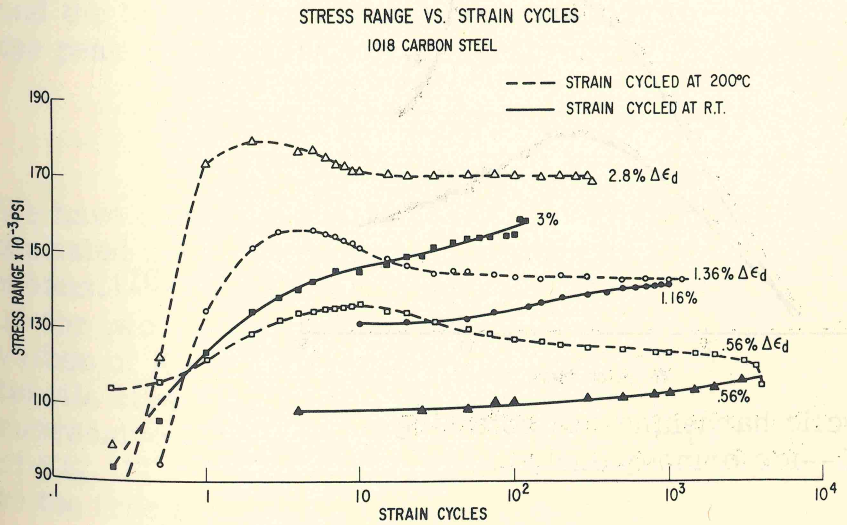


Fig. 7 Cyclic hardening at room temperature and 200°C--SAE 1111.

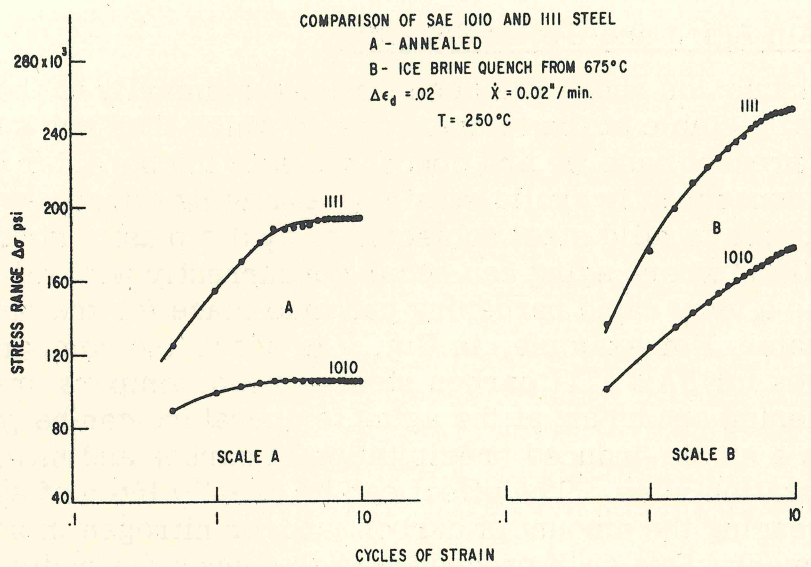


Fig. 8 Cyclic hardening--SAE 1010 and 1111--annealed and ice brine quenched.

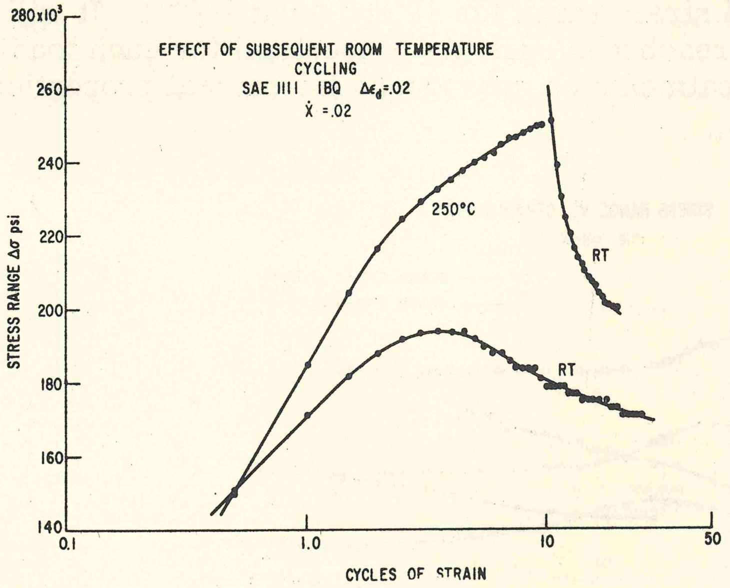


Fig. 9 Cyclic hardening and softening--SAE 1111--ice brine quenched.

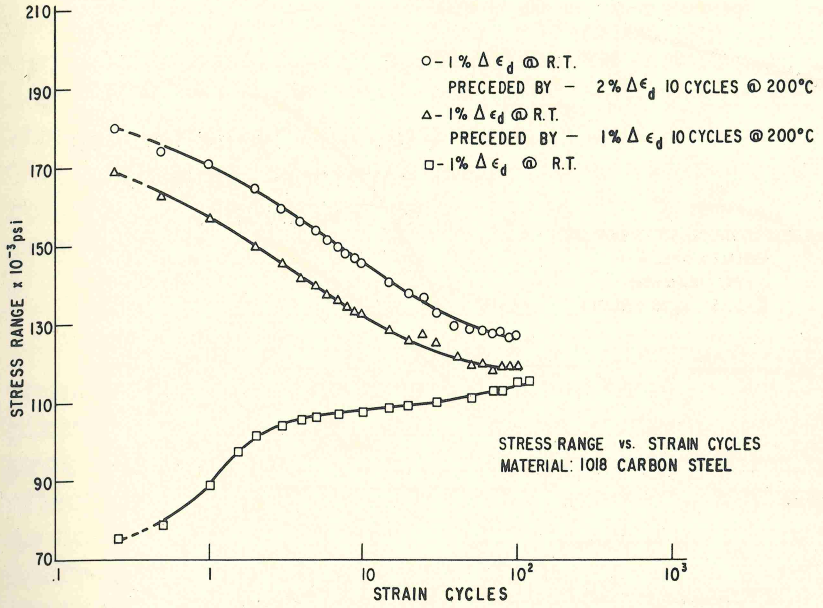


Fig. 10 Cyclic hardening and softening--SAE 1111--annealed.

C. Cyclic Tension Behavior

Another mode of straining that has been employed to examine the behavior of metals subjected to cyclic plastic strain is known as the cyclic tension test. (15) In such a test a specimen is uniaxially loaded by push-pull means and simultaneously extended monotonically. From Fig. 11 it is seen that the strain history is one involving a constant strain amplitude and a gradually increasing mean strain. A particular loading program for a cyclic tension test can be described in terms of two quantities, K_1 and K_2. K_1 is identified as the diametral strain amplitude and K_2 is the mean diametral strain per cycle. The longitudinal strain corresponding to the peak tensile load at any one point in the cyclic program can be expressed as

$$\epsilon_1 = 2K_1 + 2K_2 (N + 1/4)$$

and the longitudinal strain corresponding to the peak compressive load is defined as

$$\epsilon_2 = -2K_1 + 2K_2 (N + 3/4) \quad .$$

We have carried out a series of experiments on annealed nickel at room temperature by this means. (16) Results are shown in Figs. 12 and 13 for two distinct values of K_1 and several values of K_2. The results given are the true tensile stress and tensile strain envelopes of successive points corresponding to the loading of Fig. 11. These results can be compared to the true stress-strain curve for simple

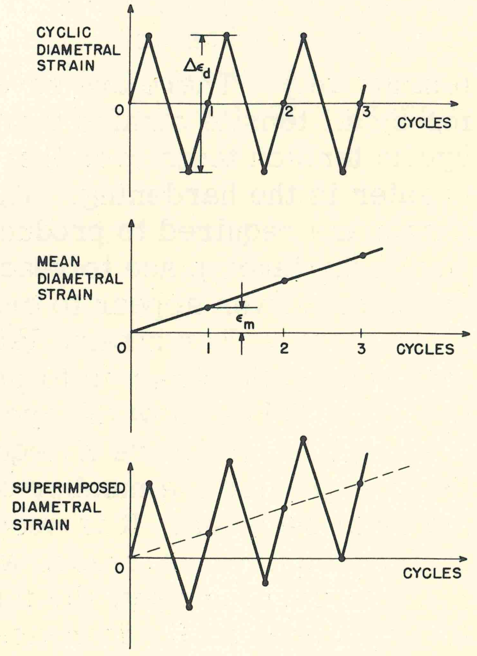


Fig. 11 Cyclic tension straining pattern.

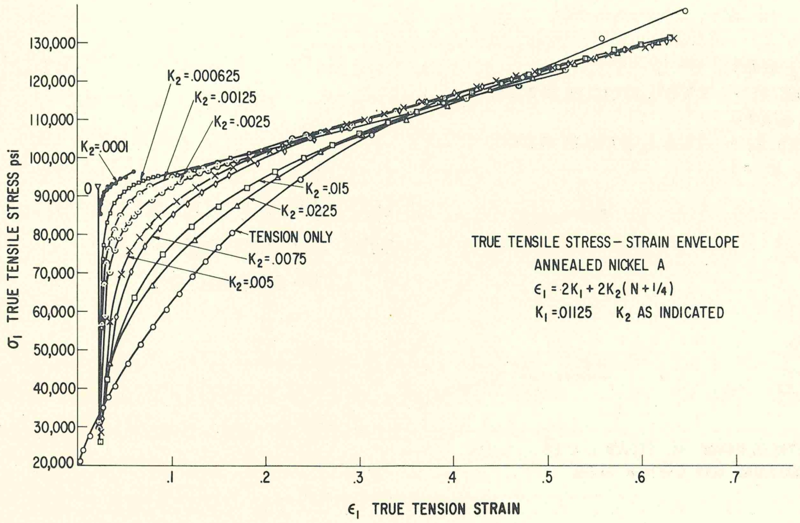


Fig. 12 Cyclic tension envelope--nickel A--K_1 = 0.01125.

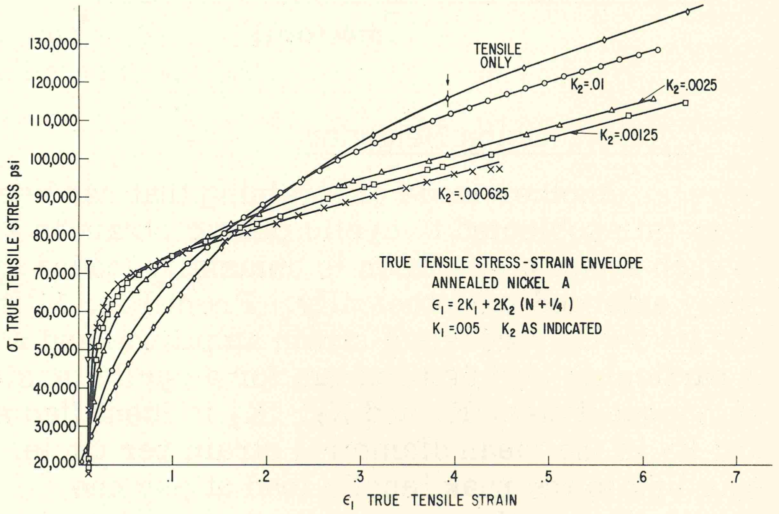


Fig. 13 Cyclic tension envelope--nickel A--K_1 =0.005.

tension only. There are several points of interest. First it will be noted that for small tensile strains there is greater hardening of the material for the cyclic tension tests over that for simple tension. The lower the value of K_2, the greater is the hardening. This is a reflection of the fact that more cycles of strain are required to produce a given mean strain, and hence more cyclic hardening takes place to reach this mean strain. It is also noted that the envelope curves appear to cross the simple tension curve at a specific value of mean strain. For strains larger than this crossover point the effect of superimposed cyclic strain is to produce an envelope curve lower than that of simple tension. This is now the cyclic softening regime. The effects are most clearly seen on Fig. 13 where K_1 equals 0.005. In the strain softening regime it appears that the greater the number of cycles to reach a particular strain the softer the material becomes. It is seen from Figs. 12 and 13 that the value of mean strain at the crossover decreases with the magnitude of cyclic strain, determined by K_1. Correspondingly, the tensile stress-strain envelope for a particular value of K_2 is lowered as K_1 decreases. It would be expected that very small values of K_1 would result in crossover points very close to zero strain, and very low values of tensile stress would be required to produce the mean strain. The cyclic tension

tests reveal, in a semiquantitative way, the degree of cyclic hardening or cyclic softening that can be expected generally in metals. The crossover point serves as an indicator of the amount of prestrain required to shift the cyclic straining process from one which hardens the material to one which softens it. The shifting of the crossover point with the cyclic strain amplitude reveals the relationship of the cyclic strain amplitude to the degree of prior cold-work in predicting whether that strain will produce cyclic hardening or cyclic softening.

D. Cyclic Strain-induced Creep

Another cyclic strain effect observed in ductile metals is the so-called phenomenon of cyclic strain-induced creep. This effect is the result of a cyclic plastic strain together with a mean stress imposed upon metals and results in a progressive deformation of the metal in the direction of the mean stress. The effect has been observed by many workers in a variety of loading systems such as controlled cyclic torsion and steady longitudinal tension in thin-walled tubes, controlled longitudinal cyclic straining and a steady torque, and controlled longitudinal cyclic straining together with a mean longitudinal stress. The phenomenon can be separated into two parts, that which can be described in terms of plasticity models involving the so-called ratcheting or shake-down type of analysis, or a second effect which relates to the metal structure itself. The subject has been reviewed in a recent paper. Some typical results are shown in Fig. 14 for annealed aluminum 1100.(17) Here the loading consists of a controlled longitudinal cyclic strain and a steady torsion. The mean shear strain that results from the mean torsion is plotted against the number of cycles of longitudinal strain for various mean torsional stresses. Results can generally be expressed as the logarithm of the mean strain vs the logarithm of the number of cycles. An explanation of the effect can be made if one views the behavior as the result of two simultaneous and separate effects. First one imagines the existence of a stabilized hysteresis loop which is produced as a result of a controlled cyclic strain with a zero mean stress. Then by the application of an added stress at the tension peak, the hysteresis loop is caused to shift in the direction of the added stress. However, continued cycling between the strain positions determined

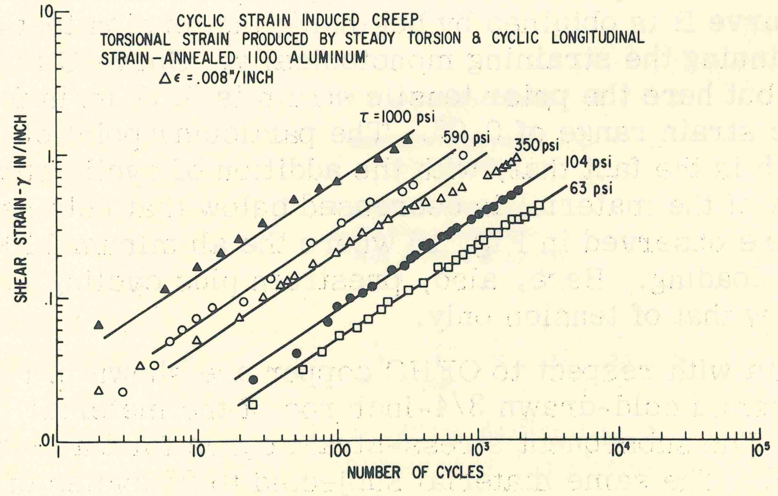


Fig. 14 Cyclic strain-induced creep--aluminum 1100--cyclic tension and steady torsion.

by the added stress results in a restabilization of the hysteresis loop and a decreased stress range (softening) until the mean stress has relaxed to zero. Reapplying the mean stress causes the loop to shift again and the process of cyclic softening reoccurs with further straining between these new limits. Thus the shifting of the loop can be viewed as a balance between strain hardening associated with the shifting of the loop and strain softening associated with the application of cyclic plastic strain.

In examining the phenomenon of cyclic strain softening after prior cold-work, or the behavior of cyclic tension tests, or the phenomenon of cyclic strain-induced creep, it would appear that these are manifestations of the same general phenomena. One would like to develop a functional relationship between the mean stress, mean strain, cyclic stress, and cyclic strain so as to be able to show these several effects as manifestations of a general behavior. However, it does not appear at this point in time that such is possible.

III. SUBSEQUENT PROPERTIES

One of the immediate questions that one might ask after reviewing the phenomenon of cyclic strain softening is the effect such strain history has on the subsequent mechanical properties of the material. If indeed the subsequent properties such as ductility and yield strength are altered in such a manner as to lower the strength and increase the ductility, then the process of cyclic straining can be viewed as a kind of a mechanical annealing treatment. The concept is not a new one. Polakowski, for example, recognized this possibility several years ago.(3) In this section we will report the results of a number of experiments that have been conducted to this end. Here the application of cyclic strain is by means of controlled longitudinal strain and the subsequent properties are determined by tensile tests.

First let us consider the results which have been obtained for 1100 aluminum, OFHC copper, SAE 1018 steel, and a 18-8 stainless steel. With respect to Fig. 15, curve A is the true stress-strain curve for annealed 1100 aluminum, curve B is obtained by straining the annealed material monotonically to a tensile strain of 0.21 per inch followed by 11 cycles of strain with a 0.06 strain range. Curve B is obtained by beginning the tension test at the mean strain position and continuing the straining monotonically. Curve C is obtained in a similar fashion, but here the prior tensile strain is 0.12 in/in followed by nine cycles of a cyclic strain range of 0.06. The particular point of interest with respect to Fig. 15 is the fact that, with the addition of cyclic strain of 0.06, the flow stress curve of the material is decreased below that obtained in simple tension. Similar results are observed in Fig. 16 where the aluminum 1100 is subjected to a compressive loading. Here, also, prestrain plus cycling lowers the flow stress curve below that of tension only.

Some data with respect to OFHC copper are shown in Fig. 17. Specimens were machined from a cold-drawn 3/4-inch rod of the material, the exact prestrain being uncertain. The subsequent stress-strain curve for this material is identified in Fig. 17 as AR6. The same material subjected to 25 cycles of strain with a 0.03 strain range develops a considerably lower flow stress curve, shown in Fig. 17 as AR10. Two facts of interest are shown in these curves. First, although the

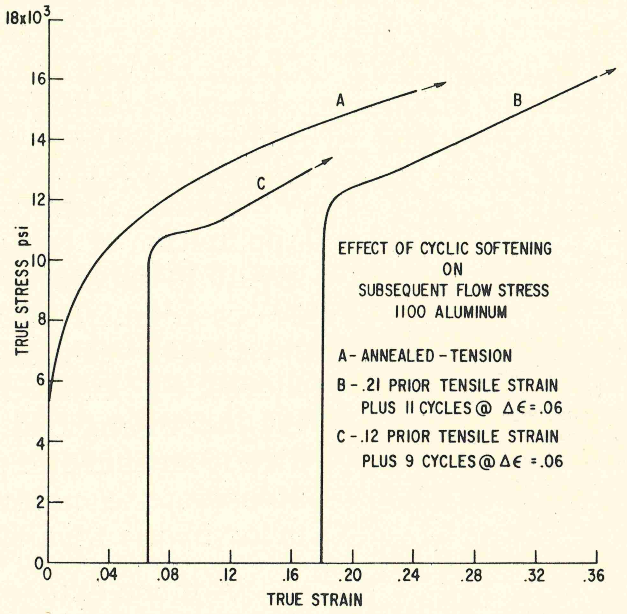


Fig. 15 Effect of cyclic softening on subsequent tensile flow stress-- 1100 aluminum.

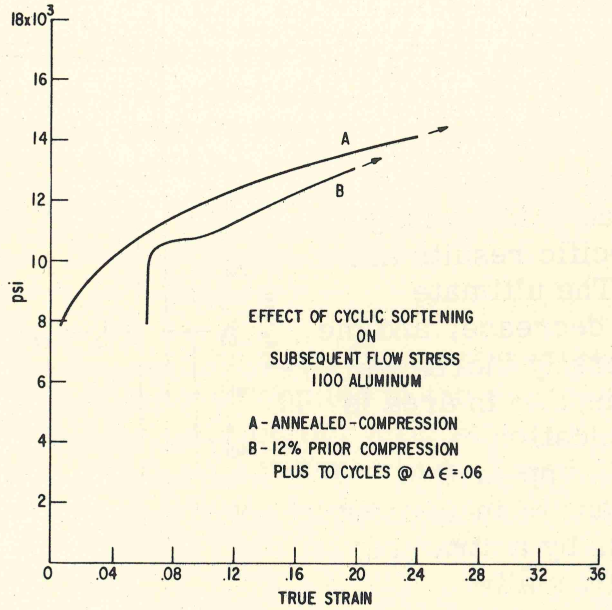


Fig. 16 Effect of cyclic softening on subsequent compressive flow stress-- 1100 aluminum.

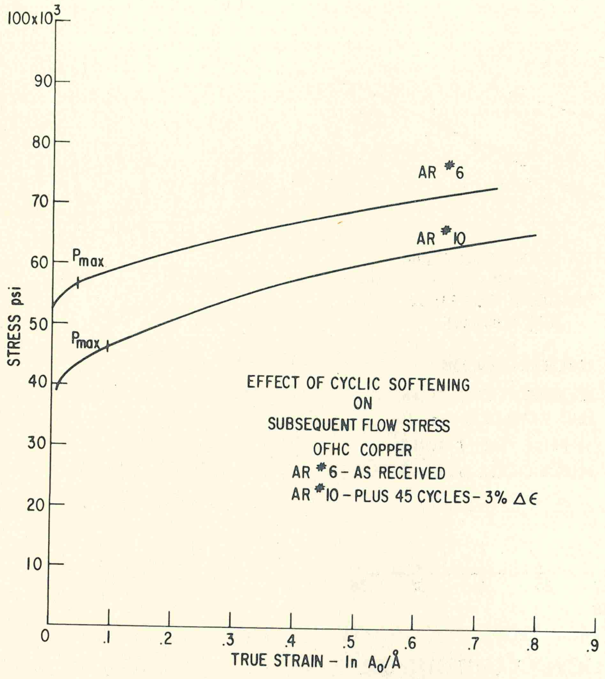


Fig. 17 Effect of cyclic softening on subsequent flow stress--OFHC copper.

shape of the curve is the same, the flow stress is significantly reduced by the influence of the prior cyclic strain. Secondly, the load at necking (indicated on each curve as P_{max}) is reduced and the strain to necking is increased by the application of cyclic strain. Since the strain to necking is a rough measure of the per cent of elongation, it is seen that the prior cyclic strain produces an increase in this quantity. Correspondingly, the maximum load (P_{max}), which is a direct measure of the ultimate tensile stress of the material, is reduced by the prior cyclic strain.

A more extensive investigation has been carried out on cold-rolled SAE 1018 steel. The straining program for the material is shown in Fig. 18. Zero strain position is defined as the state of the material in the as-received condition. A diametral strain range of 0.02 is employed and the subsequent stress-strain curve is obtained starting from the minimum strain position of 0.01. Figure 19 shows the ordinary stress-strain curves obtained after subjecting the cold-rolled steel to various cycles and strain levels as identified in the figure. It will be noted that the ordinary stress-strain curve can be altered considerably by the application of cyclic strain. The general effect, as in the case of copper, is to lower the curve and to shift the maximum load point to larger values of strain. Specific results are included in Table I. The ultimate stress is observed to decrease, and the strain to necking generally increases while the per cent reduction in area is not altered by the application of cyclic strain. It would appear that the most effective means of increasing the strain to necking is by a straining program involving a gradually decreased amplitude of strain.

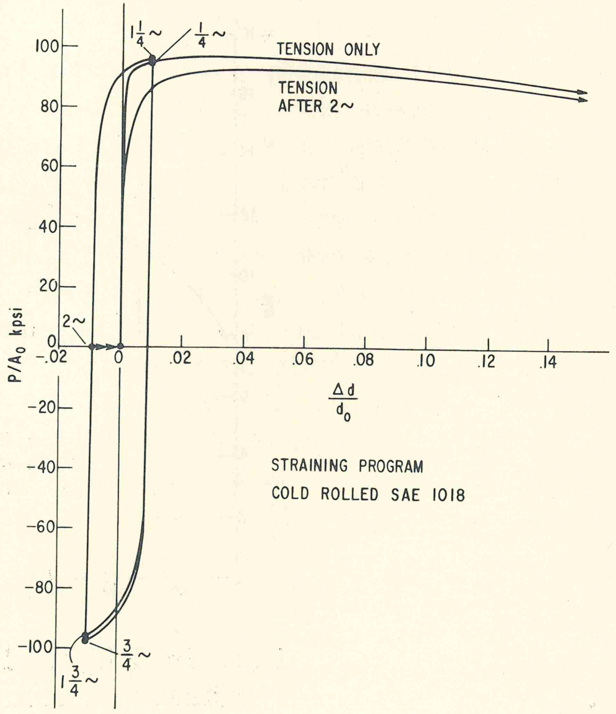


Fig. 18 Straining program--cold-rolled SAE 1018 steel.

A more pronounced effect can be obtained by subjecting the material to an even greater amount of cold work

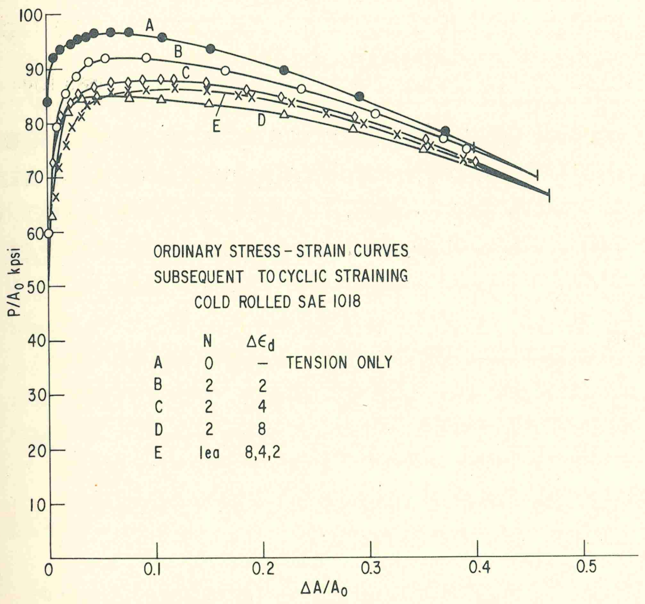


Fig. 19 Ordinary stress-strain curves subsequent to cyclic straining--cold-rolled SAE 1018 steel.

TABLE I

Effect of Cyclic Straining on Subsequent Mechanical Properties--Cold-rolled SAE 1018

Strain History	Ultimate Stress (psi)	% Strain to Necking	% Reduction in Area
As-received	94,100	6.2	44.6
+ 2~, 2% Δϵ_d	92,000	7.5	45.8
+ 2~, 4% Δϵ_d	88,000	10.6	47.1
+ 2~, 8% Δϵ_d	85,000	5.7	47.1
+ 1~, each 8, 4, 2% Δϵ_d	86,200	11.3	46.4

In Fig. 20 the results are shown on an ordinary stress-strain curve when an additional 25% longitudinal strain is applied to the cold-worked steel, followed by cyclic strain. Without the addition of cyclic straining the ordinary stress-strain curve has its maximum load at zero strain. Both the level of stress and the position of the maximum load points are changed by the addition of cyclic strain. The same data, when plotted on a true stress-strain basis, are shown in Fig. 21 and the results are summarized in Table II. The very marked increase in the per cent strain to necking is indicated in this figure, together with the substantial decrease in ultimate stress.

A series of experiments has also been conducted on annealed AISI 347 stainless steel. Under monotonic loading this material undergoes pronounced strain hardening, and therefore the effects of cyclic strain softening are of

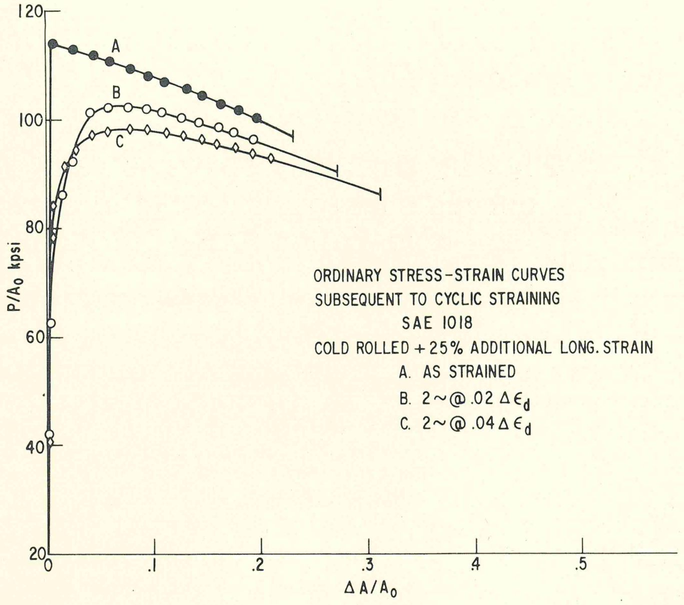


Fig. 20 Ordinary stress-strain curves subsequent to cyclic straining--SAE 1018 steel--cold-rolled + 25% additional longitudinal strain.

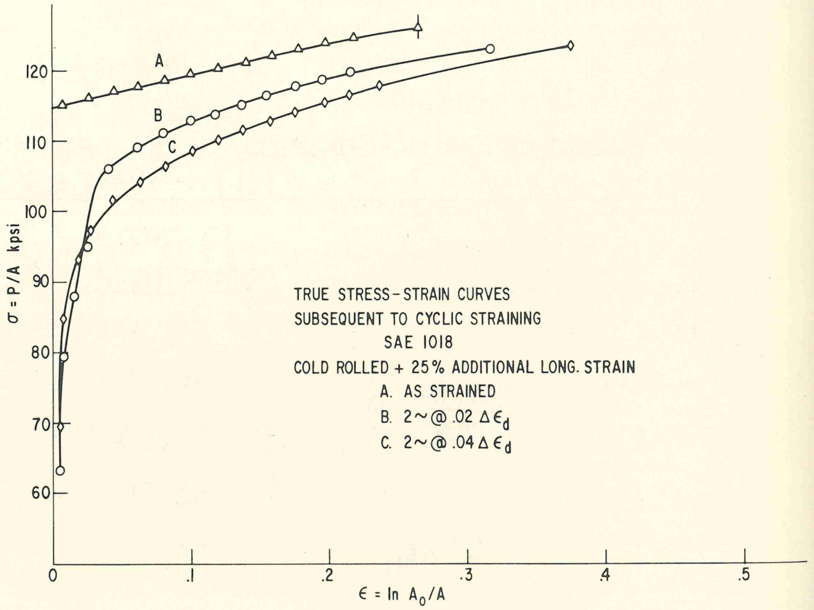


Fig. 21 True stress-strain curves subsequent to cyclic straining--SAE 1018 steel--cold-rolled + 25% additional longitudinal strain.

TABLE II

Effect of Cyclic Straining on Subsequent Mechanical Properties--SAE 1018 Cold-rolled + 25% Longitudinal Strain

Strain History	Ultimate Stress (psi)	% Strain to Necking	% Reduction in Area
As-strained	114,000	0	23.0
+ 2~at 2% $\Delta\epsilon_d$	102,500	6.8	27.2
+ 2~at 4% $\Delta\epsilon_d$	98,200	9.1	31.2

considerable interest. In Fig. 22 are shown the results of a program of push-pull cyclic straining on test specimens prestrained to a tensile strain of 0.7. The effects of various cyclic strain loadings on the subsequent flow stress curve are shown. It will be noted that the unloading and reloading curve results only in a continuation of the original flow stress curve while various amount and repetition of cyclic strain lower the magnitude of the flow stress. Specific information regarding subsequent properties from tension tests is shown in Table III. It will be noted that the strain to necking has been increased from a very low value to as high as 11 1/2% while the ultimate stress is reduced about 11% in magnitude. Save for the case where large cyclic strains are imposed on the material, there is little effect of this cyclic treatment on the subsequent reduction in area.

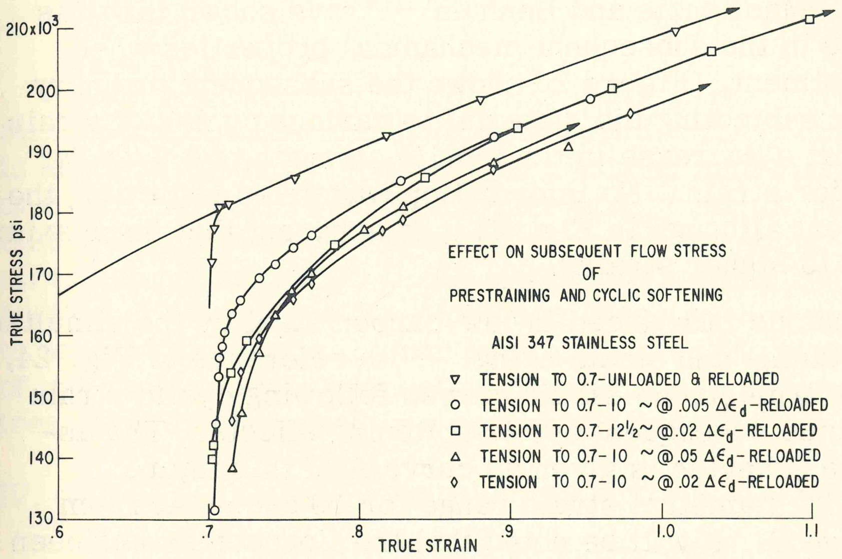


Fig. 22 Effect of subsequent flow stress on prestraining and cyclic softening--AISI 347 stainless steel.

TABLE III

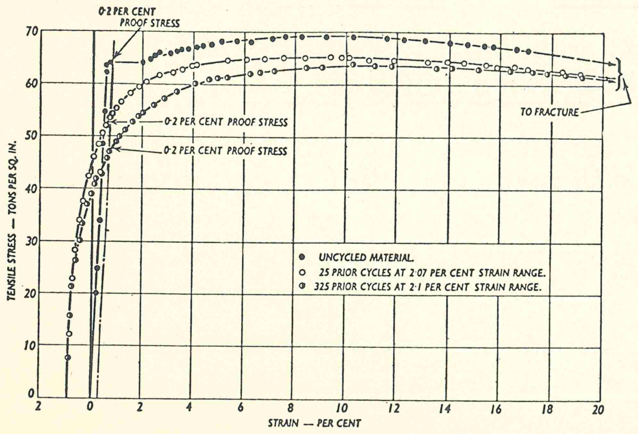
Effect of Prestraining and Cyclic Softening on Subsequent Mechanical Properties--AISI 347 Stainless Steel

Strain History	Ultimate Stress (psi)	% Strain to Necking	% Reduction in Area
Tension to 0.7 unloaded and reloaded	174,800	0.7	40.6
Tension to 0.7 10~at 1/2% $\Delta\epsilon_d$--reloaded	168,500	6.7	36.5
Tension to 0.7 12 1/2~at 2% $\Delta\epsilon_d$--reloaded	161,000	11.0	40.1
Tension to 0.7 10~at 5% $\Delta\epsilon_d$--reloaded	163,000	10.3	29.1
Tension to 0.7 10~at 2% $\Delta\epsilon_d$--reloaded	156,500	11.5	37.4

It would appear from these results that cyclic strain softening can play a significant role in modifying the subsequent mechanical properties of materials hardened by cold-work. It is seen that in general the ultimate strength is decreased and the per cent of elongation is extended over that of material in the cold-worked state, and relatively little effect is found with regard to the subsequent reduction in area. A program to optimize the necessary cyclic strain procedure in order to maximize the increase in ductility and decrease in ultimate strength has not been undertaken at the present time. It would seem, however, that the results are sufficiently significant to warrant a further investigation in this direction.

The subsequent properties of heat-treated steels subjected to cyclic strain softening is also of interest. In Fig. 6 it was shown that a heat-treated nickel-chrome-moly alloy steel (En 25) could be softened significantly by the application of cyclic strain. MacKenzie and Benham(12) have shown that this material undergoes a change in the subsequent mechanical properties when subjected to this type of treatment. Figure 23 shows the subsequent ordinary stress-strain behavior after subjecting the material to various cycles of strain of amplitude 2%. They report a decrease in the tensile strength of 8 1/2% for the case of 325 cycles of prior strain. No information was given regarding the relative ductility improvement although in Fig. 23 it is apparent that the maximum load point shifted somewhat to higher strains.

Property changes can be introduced in low-carbon steel by the simultaneous application of cyclic straining and strain aging. With reference to Fig. 24, there are shown a number of true stress-strain curves following cyclic strain aging and with and without some subsequent cyclic softening effects. The as-annealed, room-temperature behavior is given as curve A of this figure. Subjecting the material to a 2% diametral strain range for 10 cycles at room temperature, results in curve D. It will be noted that the flow stress has been increased and the point of maximum load is shifted to lower strain level. By subjecting the material to a 3% strain range at 250°C for 2 1/2 cycles followed by one cycle of 1% strain range at room temperature, one obtains curve B. It will be noted that the flow stress level has been increased significantly and the strain at maximum load point is lowered. The yield strength of this material is about twice that of the original annealed material. By subjecting the material of treatment B to 10 further cycles at a 2% strain range results in curve C. As discussed previously, the effect of cyclic softening is such as to lower the flow stress curve primarily in the low strain region. This lowers the yield stress somewhat over curve B. More significantly, however, it increases the strain to necking and hence the per cent elongation of the material. Further alterations of the stress-strain properties of mild steel can be effected by an initial quench treatment as discussed in a recent paper.(14)



Tensile stress-strain curves for uncycled and precycled heat treated En 25 steel

Fig. 23 Ordinary tensile stress-strain curves for uncycled and precycled heat-treated En 25 (Ref. 12).

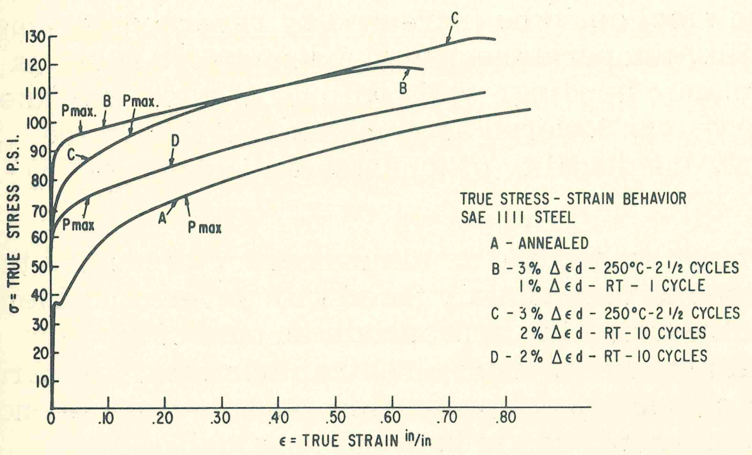


Fig. 24 True stress-strain behavior--SAE 1111--various cycling and aging treatments.

IV. TECHNOLOGICAL APPLICATIONS

The work reported above indicates that a significant change in properties can be brought about by the application of cyclic plastic strain following severe cold-working. This so-called "mechanical annealing" should have technological significance for property improvement. When considering the technological application of these results, however, one is immediately faced with the problem of finding the appropriate means for introducing cyclic plastic strain into the material. The above experiments have all been conducted on specimens that have been carefully prepared and with suitable grips for fastening to a testing machine. In application must we deal with long lengths of strip, rod, or wire, and the imposition of cyclic plastic strain on a continuous basis becomes considerably more difficult, particularly if one is interested in imposing uniform strain across the section. For wire and rod one can visualize a means whereby the rod is subjected to cyclic torsion to impose the appropriate cyclic strain for property improvement. Similarly, for sheet or strip one can imagine subjecting the material to repeated bending or unbending operations by passing the strip continuously over a sequence of rollers. It is this latter operation that we wish to discuss further in this section.

At least two investigators have explored the effects of cyclic bending of cold-worked metals on subsequent mechanical properties. Polakowski(3) has shown that ductility (measured by per cent elongation) of cold-rolled or cold-drawn aluminum, copper and steel could be increased by reversed bending. Ripling(18) finds that the nil ductility temperature of molybdenum-0.5 titanium could be lowered 60°F by cyclic plastic bending, while with TZM alloy the "knee" of the bend angle-temperature curve was lowered as much as 100°F. On the other hand, in a single experiment, the ductility of tungsten was unchanged by cyclic bending.

Assuming one has chosen cyclic bending as the means for producing the mechanical annealing treatment, one is immediately faced with several problems. These include (a) the means for introducing the appropriate amount of cyclic plastic strain, (b) the role of strain gradient, from a neutral axis strain of zero to a maximum on the outer fiber, on subsequent properties, and (c) the influence of repeated flexing about one axis on properties in both the longitudinal and transverse direction of the strip.

Let us consider first the means whereby one can cyclically flex a strip. The degree of difficulty of this problem is determined by the thickness of the strip with which one is dealing. The bending strain at the outer surface is equal to the thickness of the strip divided by the diameter of the roll around which it is bent. Thus, for example, if one is dealing with a heavily cold-worked strip 5 mils in thickness, and one wishes to impose a strain amplitude at the outer surface of 2%, a simple calculation shows that the diameter of the bending roll must be no greater than 1/4 inch in diameter. For larger bending strains, one requires even smaller diameter rolls. Hence an essential element of this problem is associated with the means whereby small diameter rolls can be supported. We have found that the so-called CBS or Contact-Bend-Stretch rolling configuration is very helpful from this point of view.(19) As shown in Fig. 25, this configuration involves the use of two relatively large and self-supporting rolls that are separated by a small gap. Resting in the cradle between the rolls is another roll of much smaller diameter which is supported uniformly along the length of the larger rolls. A strip is now threaded through this arrangement and, as tension is applied to the strip, the small roll is drawn into the gap between the two large rolls. The two large rolls are connected together by a variable-speed gear ratio, such that the strip is reduced in thickness and extended in length by exactly by the ratio of the surface speeds of the two supporting rolls. This is referred to as speed ratio control. In the present instance the speed ratio can be obtained close to one so that no reduction of strip need occur. Very small diameter bend rolls can be supported in the manner described above. For example, we have used rolls as small as 1/16 inch in diameter in order to flex a strip 1 foot in width.

A program to study the effect of cyclic softening on 0.0063-inch cold-worked steel sheet strip has been undertaken at our laboratory with the cooperation of the United States Steel Corporation. This investigation was part of a broader

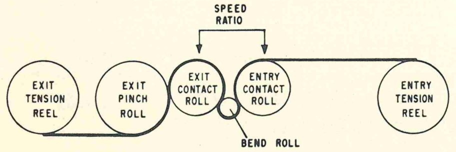


Fig. 25 Contact-Bend-Stretch rolling mill configuration.

program to evaluate the Contact-Bend-Stretch rolling process under a joint agreement between U.S. Steel and the General Electric Company.

In these experiments, the strip, identified as full hard, 55 lb basis-weight black plate and supplied by U.S. Steel, was flexed over small-diameter rolls on our 12-inch Farrel mill. This mill is a four-high, tension strip metal. The strip width was 12 inches and the threading arrangement is shown in Fig. 26. The mill was operated in such a way that the 6-inch-diameter work rolls were driven at the speed ratio of one. In other words, the mill operated as it would conventionally except for the fact that both work rolls drive in the same direction of rotation rather than in the reverse direction. Various flexing programs were carried out on the strip including flexing the strip successively over 1/8-, 1/4-, 1/2-, and 1-inch-diameter bend rolls. In some instances the strip was maintained in the threading position shown in Fig. 26, in which case the strip was bent and straightened as it passed back and forth through the mill. In other cases, the strip was rethreaded with each pass such that it could be successively reverse bent. Following a prescribed flexing program, samples typical of each processing step were cut from the strip and mechanical property tests were made at the U.S. Steel Applied Research Laboratory to determine the tensile properties, Rockwell hardness, Olsen-cup depth, fracture strength, and folding endurance. Because the strip was 12 inches in width, both longitudinal and transverse properties could be determined. Only a portion of the data is given here in the interests of space. Included are tests made by reverse flexing the strip on alternate passes over a 0.080-inch-diameter bend roll. Since the average thickness of the strip was about 0.0060 inch, the resulting amplitude of bending strain was 7.5%. With reference to Table IV, the average tensile properties and hardness of the full-hard black plate are compared with no cycling and after flexing. It is noted that a distinct increase in the per cent elongation in 2 inches occurs in the longitudinal direction. The tensile strength, correspondingly, is somewhat decreased while the yield stress at 0.2% offset is very substantially lowered. In the tangential direction, on the other hand, there appears to be very little influence of the cyclic straining. A slight decrease in the per cent elongation is to be noted, except after four passes. In other flexing programs (not reported here) it has been possible to increase the per cent elongation in the transverse direction to as high as 2% without significant change, however, in the tensile strength or yield strength of the material in that direction. In Table V are the results of this flexing program on the Olsen-cup depth, drop-weight fracture strength, and folding endurance of full-hard black plate. The Olsen-cup tests were made with a 7/8-inch-diameter ball. It will be noted that there is some increase in the drop-weight fracture strength, in the number of 180° reverse bends failure and in the number of double

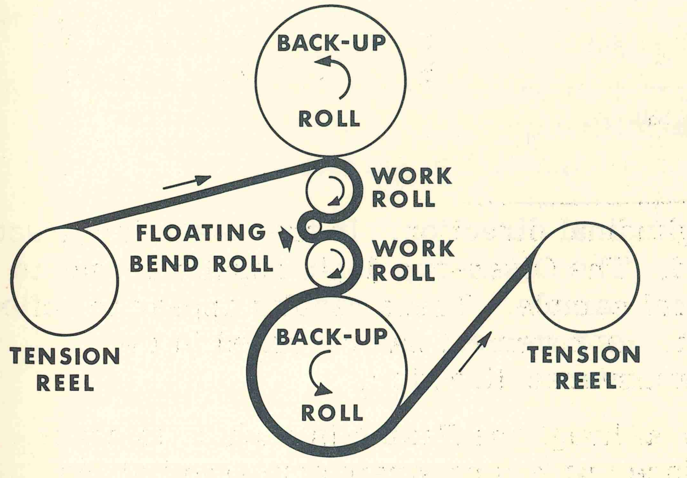


Fig. 26 Four-high rolling mill threaded for CBS rolling.

TABLE IV

Effect of Flexing on the Average Tensile Properties and Hardness of Full-hard Black Plate

Flexing Treatment	Test Direction*	Average Thickness (in.)	Yield Strength--0.2% Offset (psi)	Tensile Strength (psi)	Elongation (%)		Hardness† R30-T
					2 in.	0.01 in.	
None--Control Sample	L	0.0063	136,600	142,600	1.0	51.5	79.0
	T		133,100	147,000	1.0	16.0	
Part C--Strip Surface Reversed on Alternate Passes							
Flexed over 0.080-in-diam bend roll--first pass	L	0.0061	108,900	138,000	4.0	51.5	80.5
	T		134,600	148,000	0.5	13.0	
Flexed over 0.080-in-diam bend roll--second pass	L	.0061	107,100	137,600	4.5	53.0	80.3
	T		134,800	145,100	0.5	14.0	
Flexed over 0.080-in-diam bend roll--third pass	L	.0059	105,000	136,500	4.0	47.0	80.5
	T		133,200	145,100	0.5	13.5	
Flexed over 0.080-in-diam bend roll--fourth pass	L	.0058	103,600	137,400	3.5	52.0	80.0
	T		134,400	146,500	1.0	13.5	

*L denotes longitudinal; T is transverse.

†Each value is the average of three hardness readings.

TABLE V

Effect of Flexing on the Olsen-Cup Depth, Drop-Weight Fracture Strength, and Folding Endurance of Full-hard Black Plate

Flexing Treatment	Average Thickness (in.)	Olsen-Cup Depth* (in.)	Drop-Weight Fracture Strength (in-lb)	Test Direction†	Folding Endurance	
					No. of 180° Reversed Bends to Failure	No. of Double Folds to Failure
None--Control Sample	0.0063	0.102	6.9	L	12	2
				T	2	1
Part C--Strip Surface Reversed on Alternate Passes						
Flexed over 0.080-in-diam bend roll-first pass	0.0061	0.098	8.5	L	18	3
				T	3	0
Flexed over 0.080-in-diam bend roll--second pass	.0061	.096	8.8	L	15	3
				T	3	0
Flexed over 0.080-in-diam bend roll--third pass	.0059	.100	8.4	L	18	3
				T	3	0
Flexed over 0.080-in-diam bend roll--fourth pass	.0058	.102	8.0	L	16	3
				T	3	0

*The Olsen-Cup tests were made with a 7/8-in-diam steel ball.

†L denotes longitudinal; T is transverse.

folds to failure, all tested in the longitudinal direction. In the tangential direction the folding endurance is not improved. The Olsen-cup depth results appear to be inconclusive with respect to the control sample. These results appear to reflect the fact that the softening and ductility improvement has occurred in the longitudinal direction but not in the transverse direction.

It is interesting to note that, although the flexing is such as to cause the maximum effect on the outer surface and has no strain component at the neutral axis, nevertheless there are distinct changes in ductility and strength in the longitudinal direction. It is also interesting to note that these changes occur only in the direction of bending. In the transverse direction where the bending strain is zero there appears to be no change in the mechanical properties or the drawing or folding capabilities of the material. It would thus appear that mechanical annealing as such would be advantageous only in those cases where properties in the direction of bending are of interest. Examples would be wire, rod, bar, and in some instances strip. However, for cases where subsequent drawing operations are to be applied to the strip, it would not appear that the mechanical softening treatment is advantageous.

Improvement of transverse properties might be possible, provided the bending axis was rotated with respect to the longitudinal direction of the strip. No attempt has been made to find means for doing this; hence there are no results available.

V. SUMMARY

In summary it would appear that many metals undergo strain softening when subject to cyclic plastic strain. The degree of strain softening appears to depend upon the amount of prior cold-work or heat treatment introduced into the material, and upon the magnitude and the number of cycles of applied cyclic plastic strain. Treatments of this type appear to reduce the flow stress of the material, increase the per cent elongation, and reduce the tensile strength upon subsequent straining. The above results apply when the cyclic strains and subsequent monotonic straining are uniaxial. Tests on the flexing of strip, using the CBS rolling configuration when a strain gradient is imposed upon the material, show that significant softening effects can be introduced to heavily cold-worked steel strip in the direction coincidental to the direction of cyclic straining, but reveal no significant change in properties in the transverse direction.

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